

PHOTONICS WORKSHOP

DISCOVERING COLORS

(young professionals)

Proposed by the partners : UJM – IOGS – OpenFactory

"Discovering color" is a workshop that can be executed in Fab Labs.

Properties of this workshop:



Target audience:

University students and young professionals



Time planning: Total: 3h

0. Basics of colorimetry (20mn)
1. Constructing a light box (60mn)
2. Color and spectral analysis of materials (30mn)
3. Spectral analysis of the light box (2 x 20mn) AND Color analysis of the light box (2 x 20mn) (40 mn)
4. To go further (30 min)



Estimation cost:

Paper, labels, inks 50€

LED ribbons and supplies: 50 €

Spectrophotometer : 1200 € (The spectro is to be bought once)

Step 0 : a little bit of colorimetry

- Basics of colorimetry

Color is not a physical phenomenon, but a complex sensation produced by the brain (similarly to sound or touching). It is therefore not directly measurable, and often difficult to assess objectively. However, the color of lights in a black environment is the easiest to quantify thanks to the rules of colorimetry (the proper color of objects is much more difficult to characterize).

The rules of colorimetry rely on the observation that 3 primaries are enough to reproduce all light colors (except, in practice, nearly-monochromatic light whose spectral power distribution is concentrated around one particular wavelength).

Every color can therefore be quantified by the respective powers of three primaries.

The Commission Internationale de l'Eclairage which created the color assessment standard proposed the three following primaries : monochromatic red light of wavelength 700 nm, monochromatic green light of wavelength 546.1 nm, and monochromatic blue light of wavelength 435.8 nm. From the color experiments carried out with observers by mixing these primaries, a color space called the CIE 1931 RGB color space has been created, that is now at the base of almost all activities in color science. They also proposed a derivative of this color space, more convenient and more used, called the CIE 1931 XYZ color space.

Step 1 : Constructing a light box

The light box is a convenient way of producing rather homogenous lighting system made of various lamps (e.g., colored LEDs), as an integrating sphere. It aims at mixing the lights emitted by the three LED ribbons as homogeneously as possible and avoid colored halos on the ceiling of the box where the colors will be analyzed. For that purpose, white diffusing panels are strongly recommended.

The lighting system should contain three LEDs red, green and blue; the intensity of each one should be varied continuously from 0 (no light emission) to 1 (maximal light emission).

- **Step 1.1 - Part list**

The lighting system is on the base of the light box.

1. Wood panel, 5mm thickness

2. Tape
3. Wood glue
4. Electric wire : black, red, blue and green
5. Dimmer x 3
6. Connector strip
7. Double-sided tape
8. Screw
9. White paint
10. Brush
11. Cutter
12. Wood saw
13. A small plexiglass pannel, 10cm x 14cm
14. Light scattering paper
15. Electric drill with 2cm broach tool
16. 12v adapter
17. Power cable
18. RGB Led ribbon
19. Soldering iron

- **Step 1.2 - Cutting the wood**

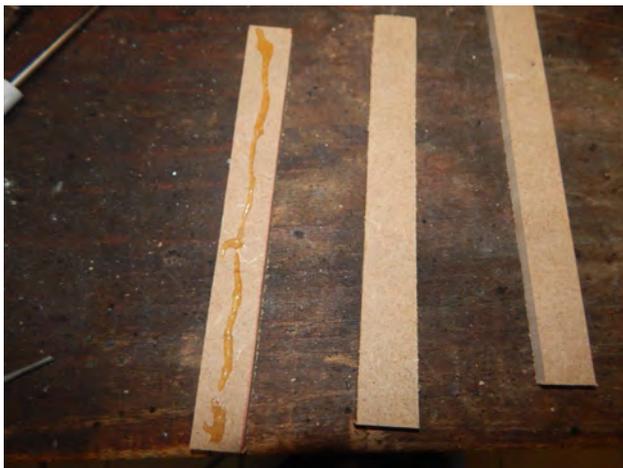
Trace on your woods pannel :

- One rectangular of 18cm by 30cm
- Three square of 18cm
- One square of 17,5cm
- Six rectangular of 2cm by 18cm
- One rectangular of 16cm by 17cm

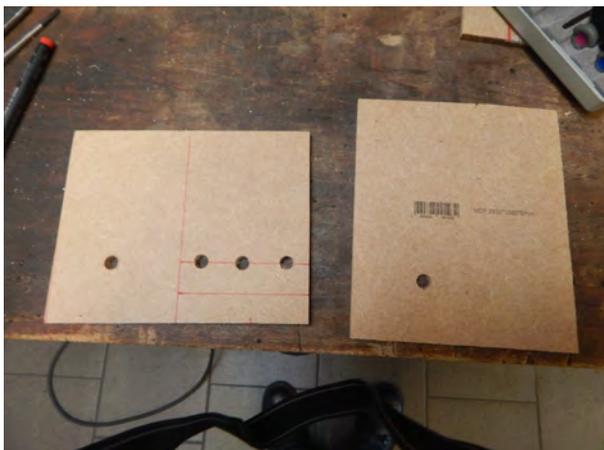
- **Step 1.3 - Assembling the light box**



Place and screw the dimmer on the 18 x 30 cm wood panel.



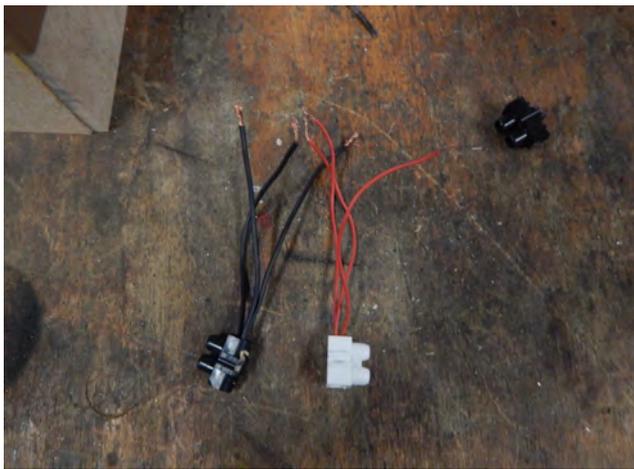
Glue together 3 of the 18cm by 2cm wood panel, to make support for the light box. Repeat again.



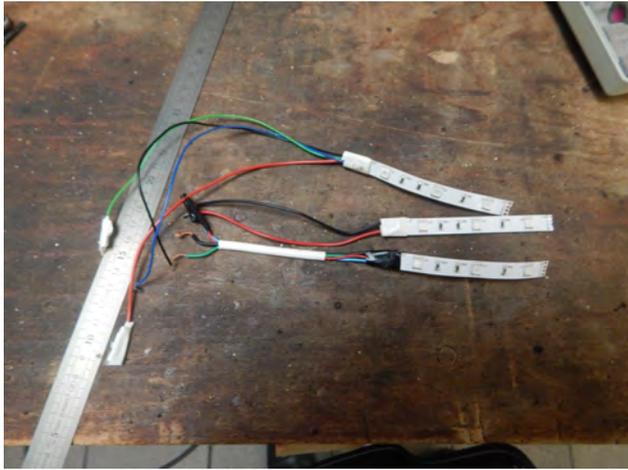
Drill 4 holes in the 17,5 cm square, as above, at 4cm from a side. You will pass the electric wire by these holes. In a 18cm square, drill another hole to pass the power cable.



Glue the wood support, then the wood pannels around the support. The wood pannel with 4 holes near the dimmer, and that with one hole at the opposite side. Waiting the glue to dry, fix the pannels with tape. Place the 12v adapter in the box. Connect with the power cable.

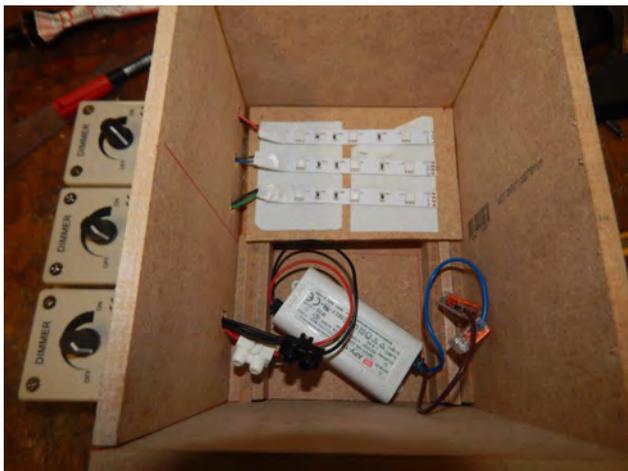


Cut 3 small wire in the red and in the black wire. Connect them in two different connector strip then to the adaptor, then to the dimmer. The black wire are for the (-) and the red for the (+)

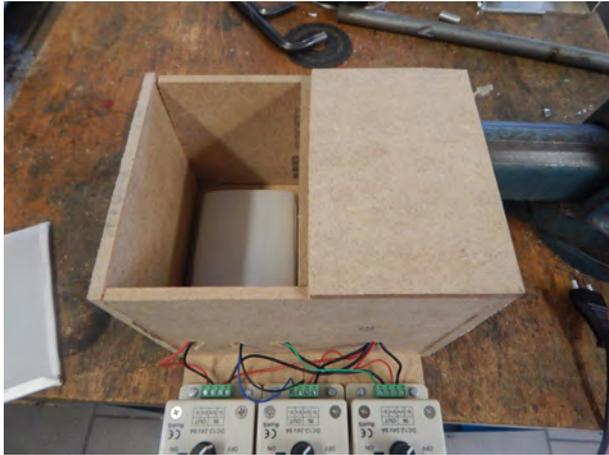


Cut 3 small wire in the red, blue and green wire. Do it again with the black wire, then connect each of them to 3 small LED ribbon with the soldering iron. So you have a red LED ribbon, a blue LED ribbon and a green LED ribbon.

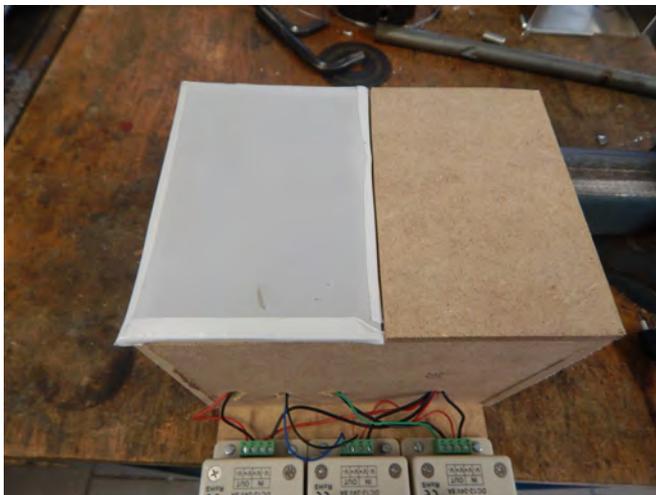
Place some double-sided tape at the bottom of the box. Fix your LED ribbon and pass your wire trough the hole.



Connect your ribbon to the Dimmer : the black wire on the (+) and the red, blue or green wires to the (-).



Fold a piece of light scattering paper around the LED ribbon and fix it on the double-sided tape. Place the last wood panel in the box, near the LED ribbon and the last one on the top.



Fold a piece of light-scattering paper around the plexiglass and fix it with tape.

Step 2 : Color and spectral analysis of materials

This aims at understanding the color of absorbing materials, absorption being at the origin of the color of most objects. The materials can be painting or dyes.

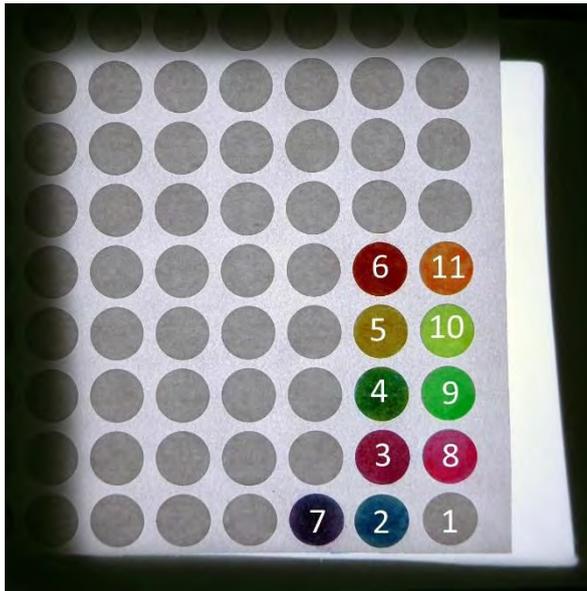
We especially recommend cyan, magenta and yellow inks because they absorb light in on specific part of the visible spectrum: cyan absorbs red light, magenta absorbs green light and yellow absorbs blue light. These colors cyan, magenta and yellow are the primary colors used in printing; they can therefore be found in printer cartridges (see figure below).

We also propose to analyse fluorescent inks, easily available through highliners.



Figure: (left) cyan, magenta and yellow well-worn inkjet cartridges used to produce the colored samples, by collecting some ink with a paintbrush; (right) Fluorescent highliners

Place the colored objects on top of the lightbox; they are therefore backlit. In order to avoid any opacity issue, we advise the use of pieces of paper (or paper labels as in the figure below) colored with the different inks.



1. White (undyed label)
2. Cyan ink
3. Magenta ink
4. Green (mixture of cyan and yellow inks)
5. Yellow ink
6. Red (mixture of yellow and magenta inks)
7. Blue (mixture of cyan and magenta inks)
8. Fluorescent magenta ink
9. Fluorescent green ink
10. Fluorescent yellow ink
11. Fluorescent orange ink

Figure : Paper labels deposited on top of the light box, illuminated by white light (maximal power for the three primaries). The labels on the bottom right have been died by inks.

Observe the color of the different inks when illuminated by the red, green and blue primary light, then by the yellow, magenta and cyan secondary lights. Try to deduce which range of wavelengths each ink absorbs more light.

For example, we see in the figure below that all the color patches containing cyan, as well as the green fluorescent ink, look dark under red light. It therefore means that cyan ink and fluorescent green ink strongly absorb red light (large wavelengths).

Similarly, under green light, the patches containing magenta ink look darker, and those containing cyan ink are look darkened to a lower extent. We can deduce that magenta ink strongly absorb green light (medium wavelengths) and cyan ink is also slightly absorbing in this spectral range...

Finally, observe the colors under blue light. The patches containing yellow ink are darker, thus indicating that yellow ink absorbs blue light (smaller wavelengths). We also observe that the fluorescent inks get some colors...

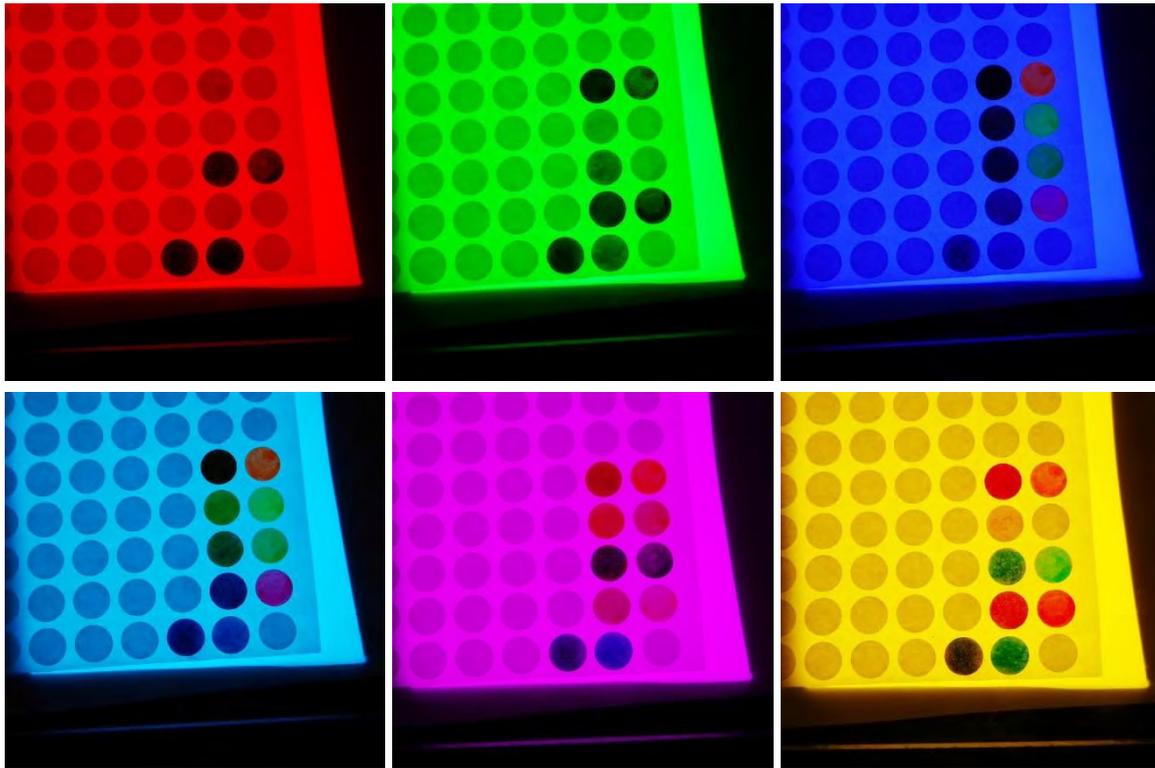


Figure : Colored labels illuminated by (from top to bottom, left to right) : red, green, blue primary lights, and cyan , magenta and yellow secondary lights.

- **Spectral verification of the absorbance of the inks**

The spectrophotometer enables measuring the spectral transmittance (fraction of light that is transmitted for each wavelength) of the samples.

First measure the spectrum of the white label by placing the edge of the optical fiber on it. This spectrum will be considered as the reference spectrum $S_{ref}(\lambda)$.

Then, place the edge of the optical fiber on a colored label, and measure the spectrum $S(\lambda)$. The spectral transmittance of this colored label is defined as

$$T(\lambda) = S(\lambda) / S_{ref}(\lambda)$$

Notice that the SpectraSuite software has an option permitting to save the spectrum $S_{ref}(\lambda)$ as reference spectrum, then operating the division by it on every further spectrum, in real time. Hence, every subsequent spectrum measured in this mode are between 0 and 100% for all wavelengths.

<Insert screen capture for illustration>

Verify the supposition previously made concerning the absorbance of the cyan, magenta,

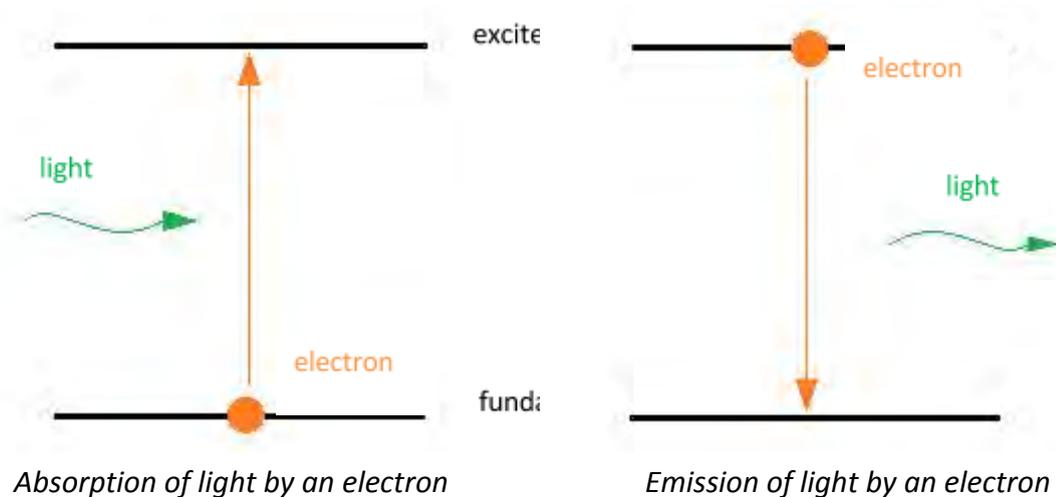
and yellow inks.

- **Spectral analysis of the fluorescent inks**

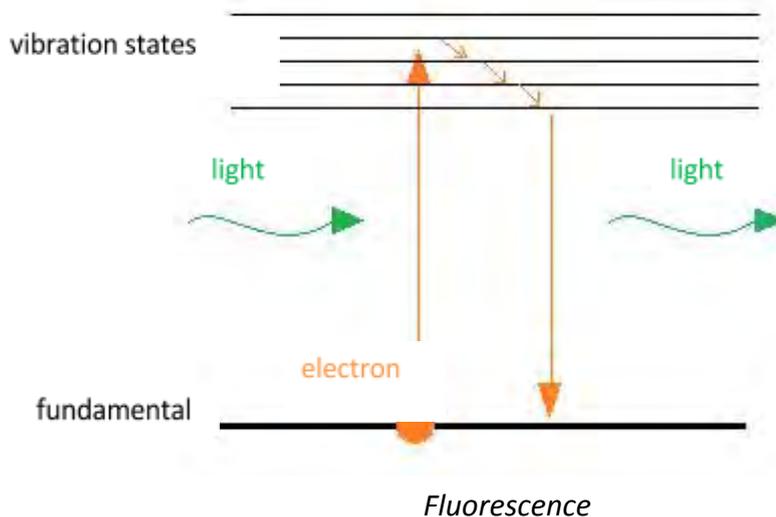
Pursue the spectral transmittance measurements by considering now the labels dyed with fluorescent inks. We observe that they absorb light in certain wavelength domains, but their transmittance also overpasses 100% in other wavelength domains, which are always on the right in the spectral graph in respect to the absorbance domain. This is characteristic of fluorescent material, able to absorb some luminous energy and reemit part of this energy under the form of less energetic light.

- **About Fluorescence**

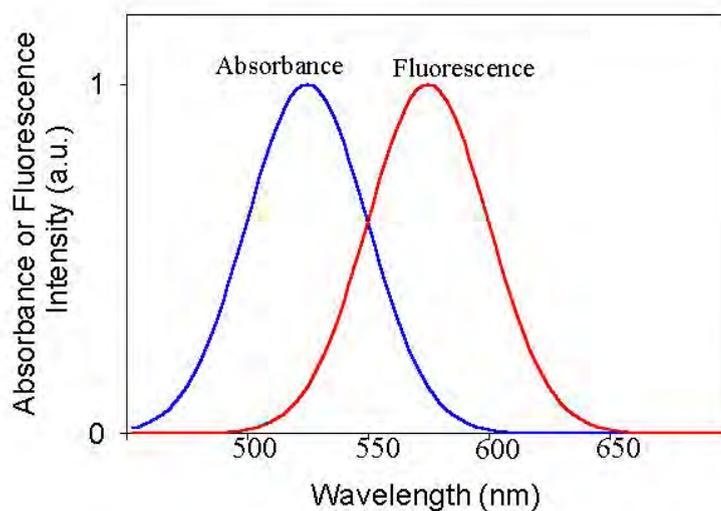
The emission of light by an atom is an electronic phenomenon. As long as an object is at rest, its electrons are at fundamental state. When the light strikes the surface of this object, it gives a certain energy E to the electrons, so they move from fundamental state to an excited state by absorbing this energy. These electrons tend to very quickly return back to fundamental state by losing the energy absorbed in the form of a light radiation of energy E . That is what we call spontaneous emission.



Fluorescence is a specific case of light emission. The excited state of an atom is composed of many vibration states. In the case of spontaneous emission, the excited electron moves from one vibration state to the fundamental state. In the case of fluorescence, the electron goes through several vibration states before returning to its fundamental state.



As a consequence, fluorescence is a process on which an atom absorbs light at a specific wavelength and re-emits this light at the same or at another wavelength. In most cases, the emitted light has a longer wavelength and a lower energy than the absorbed radiation.



Step 3 : Spectral analysis of the light box

- Use a spectrophotometer, preferably with optical fiber, and software for simultaneous display of the spectral measurements, or example the USB-650 spectrophotometer from Ocean Optics (USB supply) and SpectraSuite software.

- Place the optical fiber on top of the light box.
- Verify that the spectral acquired by the spectrophotometer does not vary when the edge of the fiber is rotated or moved on the ceiling of the light box. Otherwise, fix it so that all measurement are performed in the same acquisition conditions.

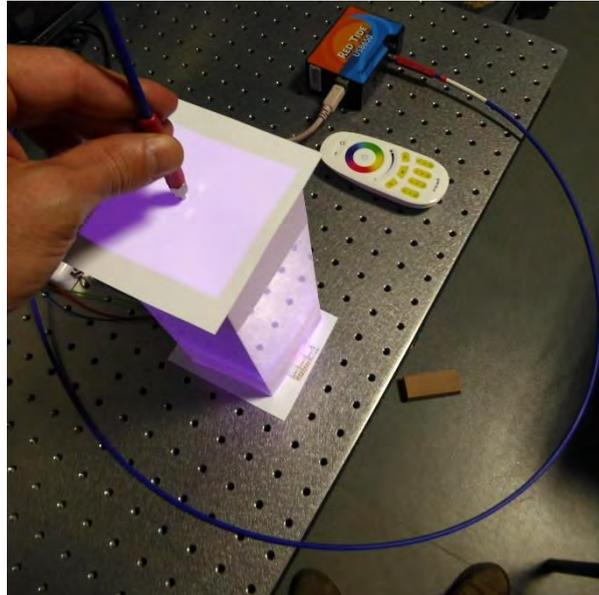


Figure: Spectrophotometer (orange and blue box) with optical fiber; the edge of the fiber is placed on the ceiling of the light box.

- The SpectraSuite software displays the measured light spectrum in real time as shown below.

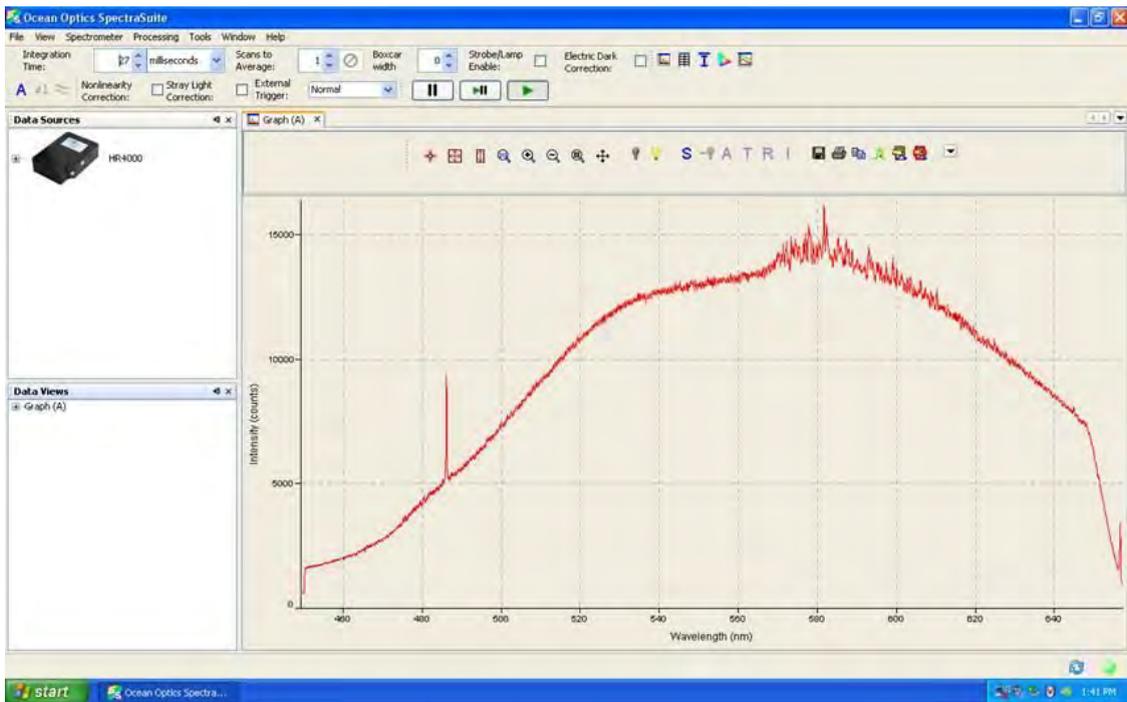


Figure: Measured spectrum as displayed by the SpectraSuite software.

- **Primaries** - Measure the spectrum of the red light only (ribbon of red LED at maximal power, other ribbons turned off). Then measure the spectra of the green and blue lights respectively. These red, green and blue light will be called *primaries*.
- **White** - Measure the spectrum of the white light (red, green and blue LED ribbons at maximal power) and verify that the obtained spectrum is the sum of the three previously measured spectra of primaries.
- **Secondary lights** - Measure the spectrum of the light obtained by tuning on two primaries (at maximum power) and turning off the third one.

Secondary light	Red primary	Green primary	Blue primary
yellow	On	On	Off
Magenta	On	Off	On
Cyan	Off	On	On

In each case, verify that the measured spectrum of the secondary light is the sum of the measured spectra of the two corresponding primary lights.

- **Other lights**

Mix different amounts of red, green and blue primaries. Verify that the spectrum of the

obtained light is a linear combination of the spectra of the primaries.

Step3 bis : Color analysis of the light box

Meanwhile, explanations about the analysis of colours.

- Tristimulus values

In the CIE 1931 XYZ color space, every light can be attributed 3 values called “tri-stimulus values” that characterize its color as perceived by a “standard observer” all around the world. These tristimulus values X, Y, and Z are computed from the spectrum of the light, $C(\lambda)$, defined in steps of 5 nm from 380 to 780 nm (the human visual system being sensible only to these wavelengths):

$$X = \frac{1}{k} \sum_{\lambda} C(\lambda) \bar{x}(\lambda)$$

$$Y = \frac{1}{k} \sum_{\lambda} C(\lambda) \bar{y}(\lambda)$$

$$Z = \frac{1}{k} \sum_{\lambda} C(\lambda) \bar{z}(\lambda)$$

with

$$k = \sum_{\lambda} C(\lambda)$$

The functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ have been derived from psychovisual experiments and tabulated (see table available at:

<https://drive.google.com/file/d/0B6DGCSLfElgONzhwX1RLbWJtQ1E/view?usp=sharing>).

- Chromaticity

When the three primaries are supplied by maximum power, we obtain a certain white color. When the three primaries are supplied by half the maximum power, we obtain the same white color, but less intense. The fact that the perceived color is independent of the power

of the light is specific to lighting and does not apply to the color of objects: an object that reflect a less intense light signal will be perceived as darker (for example a white object is perceived as grey if it is less reflecting).

Hence for light, the notion of *lightness* (black corresponding to lightness zero, and white to lightness maximal) makes no sense. We are more interested by the notion of hue (red, orange, yellow, green...) and chroma (the colorfulness that can vary from very chromatic for monochromatic lights, to achromatic for white or grey). For the specification of these two informations, a 2D graph suffices, called chromaticity diagram.

The chromaticity values x , and y of a given light are computed from its X , Y , Z tristimulus values:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

The chromaticity of every light signal can therefore be displayed in the chromaticity diagram displayed below.

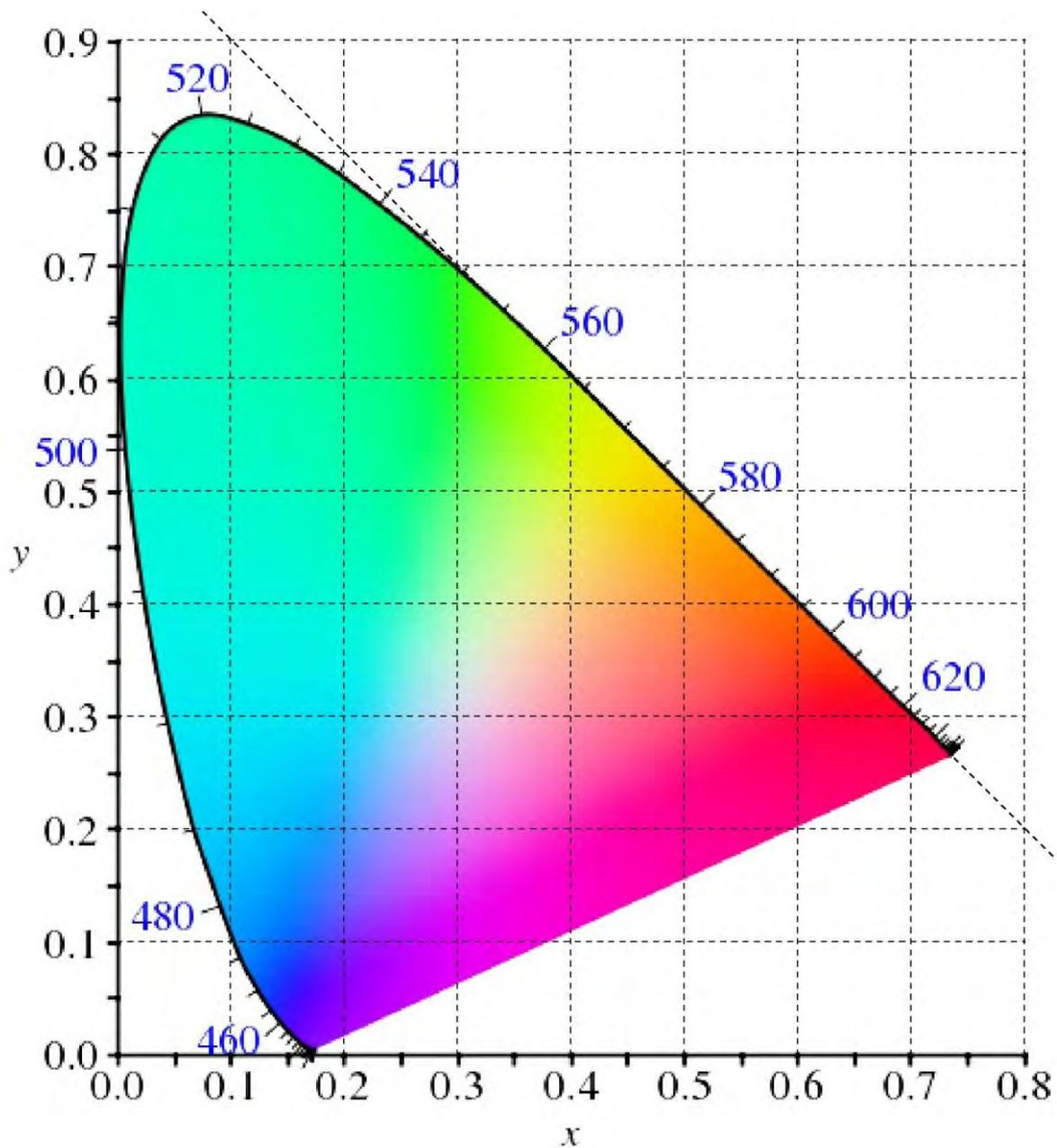


Figure: CIE 1931 xy chromaticity diagram.

- Computing the chromaticity of the light box

By choosing a certain power for each of the three primaries (LED ribbons of the light box), we obtain a certain light signal whose spectrum is measured by using the spectrophotometer.

The SpectraSuite software enables automatic color calculation from measured spectra, in particular the CIE 1931 xy chromaticity values. The values are also displayed automatically in the chromaticity diagram.

<Insert screen capture for illustration>

Alternatively, by using the formulas above and the tabulated color matching functions, we can compute the X,Y,Z tristimulus values then the x, y chromaticity values, and place them manually on a printed copy of the chromaticity diagram.

- Color gamut

The set of reproducible colors by a lighting system relying on three colored lamps is limited. This set is called “color gamut”. We can show that it is represented by a triangle in the chromaticity diagram, whose vertices are the chromaticity points of the three primaries.

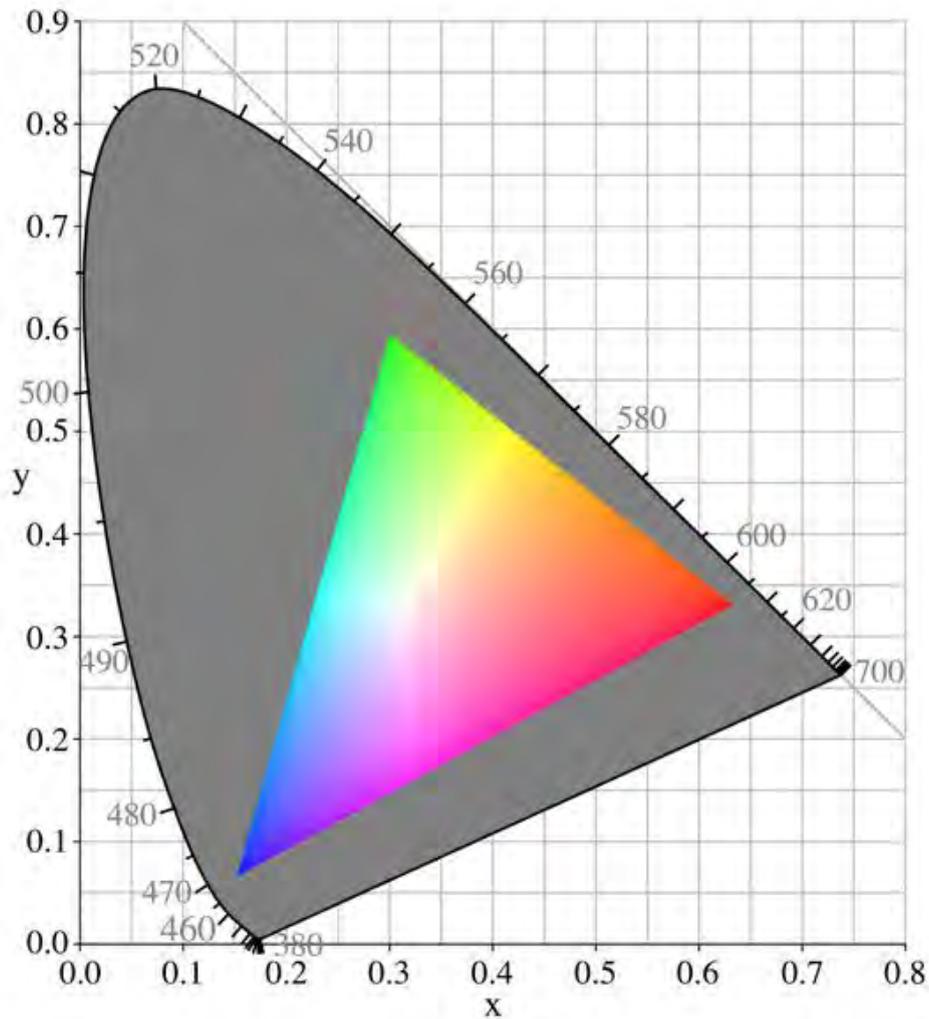


Figure : example of color gamut corresponding to a CRT display.

In order to verify that the color gamut of the light table is a triangle, compute the chromaticity point associated with each of the three primaries and place it in the chromaticity diagram.

Then, turn off one LED (for example the blue LED) and acquire various spectra by varying the respective powers of the two other LEDs. For each acquired spectrum, compute the chromaticity points and verify that they are aligned on one edge of the triangle.

Finally, by choosing different amounts of the three lights red, green and blue, verify that the obtained chromaticity points are always inside the triangle.

- Reproducing the color of illuminants

Some characteristic lightings such as daylight or tungsten lamp light are considered as standards in color science. The CIE therefore defined various lighting systems, called “standard illuminants”. To each of them is attributed a spectral power distribution, and thereby tri-stimulus values and chromaticity values, given in a table available here: <https://drive.google.com/file/d/0B6DGCSLfEIgOcWRKbIBUVFBLdVlk/view?usp=sharing>

Below is a table of the main illuminants:

- A : Tungsten lamp : blackbody radiator at 2856 K
- B and C : Daylight-simulating SPDs
- D50 – Daylight, early morning (CCT = 5000 K)
- D65 – Daylight, overcast (CCT = 6500K)
- E : Equal energy
- F series – Fluorescent lamps

Step 4 : To go further

- Your own DIY spectrophotometer : <https://spectralworkbench.org/>
- Come again with your kids to another workshop for:
 - 10-14 years
(<https://drive.google.com/open?id=0By46u8jim7GZOTl6MGNEQkdfRms>) or
 - 15-18 years
(<https://drive.google.com/open?id=0By46u8jim7GZVDdsZWZXX2RtWTQ>)

The logo for PHABLABS 4.0 features a stylized blue and orange sunburst icon on the left, followed by the text "PHABLABS 4.0" in a bold, blue, sans-serif font.

PHABLABS 4.0 is a European project where **two major trends** are combined into one powerful and ambitious innovation pathway for digitization of European industry: On the one hand the growing awareness of **photonics** as an important innovation driver and a **key enabling technology towards a better society**, and on the other hand the **exploding network of vibrant Fab Labs** where next-generation **practical skills-based learning** using KETs is core but where photonics is currently lacking.

www.PHABLABS.eu

This workshop was set up by the *Institut d'Optique Graduate School and University Jean Monnet de Saint-Etienne* in close collaboration with *OpenFactory*.



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